The Very Long Baseline Neutrino Oscillations Experiment

Presented to
FCP05 Neutrino Session

by
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Nashville, TN
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Physics Case for the VLBNO Experiment

- **_All parameters_ of neutrino oscillations can be measured in _one_ experiment**
    - every one of the oscillation parameters is important to particle physics
    - the oscillation parameters contribute to important cosmology questions
    - a ν_e *appearance* experiment is required to determine _all_ the parameters
    - a *broadband Super Neutrino Beam* at _very long distances_ is the key to success
    - the *Very Long Baseline Neutrino Oscillation* (*VLBNO*) Exp. is the best method

- **The massive VLBNO detector empowers _additional forefront physics_**
    - a powerful next-generation *Nucleon Decay* search
    - supernova and relic neutrino searches
    - a deep underground detector in the prospective *NSF DUSEL* is ideal for VLBNO

- **The CP-violation parameter δ_{CP} is the most difficult number to determine**
    - matter effects interact with CP-violation effects
    - the CP-violation phase δ_{CP} has distinct effects over the _full 360º range_
    - antineutrino running offers a complementary way to demonstrate CP-violation
      and may be pursued at a later stage of VLBNO as needed for physics

- **The off-axis beam approach requires multiple distances and detectors**
    - all experiments will require of order 10 Snowmass years of running
    - multiple detectors and beams will require careful control of systematic errors

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Questions About the VLBNO Experiment

Won't Hyper-K + a 4MW J-PARC beam complete all the measurements?
- no, the 295km T2K baseline is too short for the solar term and matter effects
- the off-axis T2K neutrino beam requires at least one other big experiment
  plus long antineutrino running to determine d_{CP} without ambiguities

Isn't VLBNO much more expensive than other approaches?
- the VLBNO cost is *comparable to or lower* than other less complete methods
- the VLBNO detector can be made in ~100kTon steps, phased over time
- VLBNO plans to share the large *Nucleon Decay Detector* in *NSF's DUSEL*

What about the background from p^0 inelastic events in VLBNO?
- sophisticated Monte Carlo simulations with state-of-the-art Super-K pattern
  recognition and maximum likelihood methods have mitigated this issue

Why not determine CP-violation with antineutrino running?
- antineutrino measurements will require of order 10 Snowmass years of running
- the antineutrino running may be of value to a long-running DUSEL experiment

Isn't the AGS at BNL needed for RHIC and RSVP?
- RHIC runs very compatibly with AGS and RSVP won't use all the available time
  (RSVP is planned to run for 25 weeks/year for 5 years)
- the neutrino oscillation/nucleon decay experiment could last many years

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Electron Neutrino Appearance by Oscillation in Vacuum

The equation for oscillation[a] of $\nu_\mu \to \nu_e$ neutrinos in vacuum is given by:

$$P(\nu_\mu \to \nu_e) = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(\Delta m^2_{31} L/4E_\nu) \qquad \text{'Term 1'}$$

$$+ \tfrac{1}{2} \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \cos(\theta_{13}) \times$$
$$\sin(\Delta m^2_{21} L/2E_\nu) \times [\, \sin(\delta_{CP}) \sin^2(\Delta m^2_{31} L/4E_\nu)$$
$$+ \cos(\delta_{CP}) \sin(\Delta m^2_{31} L/4E_\nu) \cos(\Delta m^2_{31} L/4E_\nu) \,] \qquad \text{'Term 2'}$$

$$+ \sin^2(2\theta_{12}) \cos^2(\theta_{13}) \cos^2(\theta_{23}) \sin^2(\Delta m^2_{21} L/4E_\nu) \qquad \text{'Term 3'}$$

+ matter effects + smaller terms

$$\Delta m^2_{31} \equiv m^2_3 - m^2_1 = \Delta m^2_{32} + \Delta m^2_{21} \sim \Delta m^2_{32}$$

What do we learn by contemplating this long algebraic expression?

- **simple inspection won't reveal all the many experimental implications**
- **detailed calculations are needed to clarify the important experimental issues**
- **key oscillation parameters still to be determined are shown in red**
- **the known oscillation distance scales in green are exploited by VLBNO**

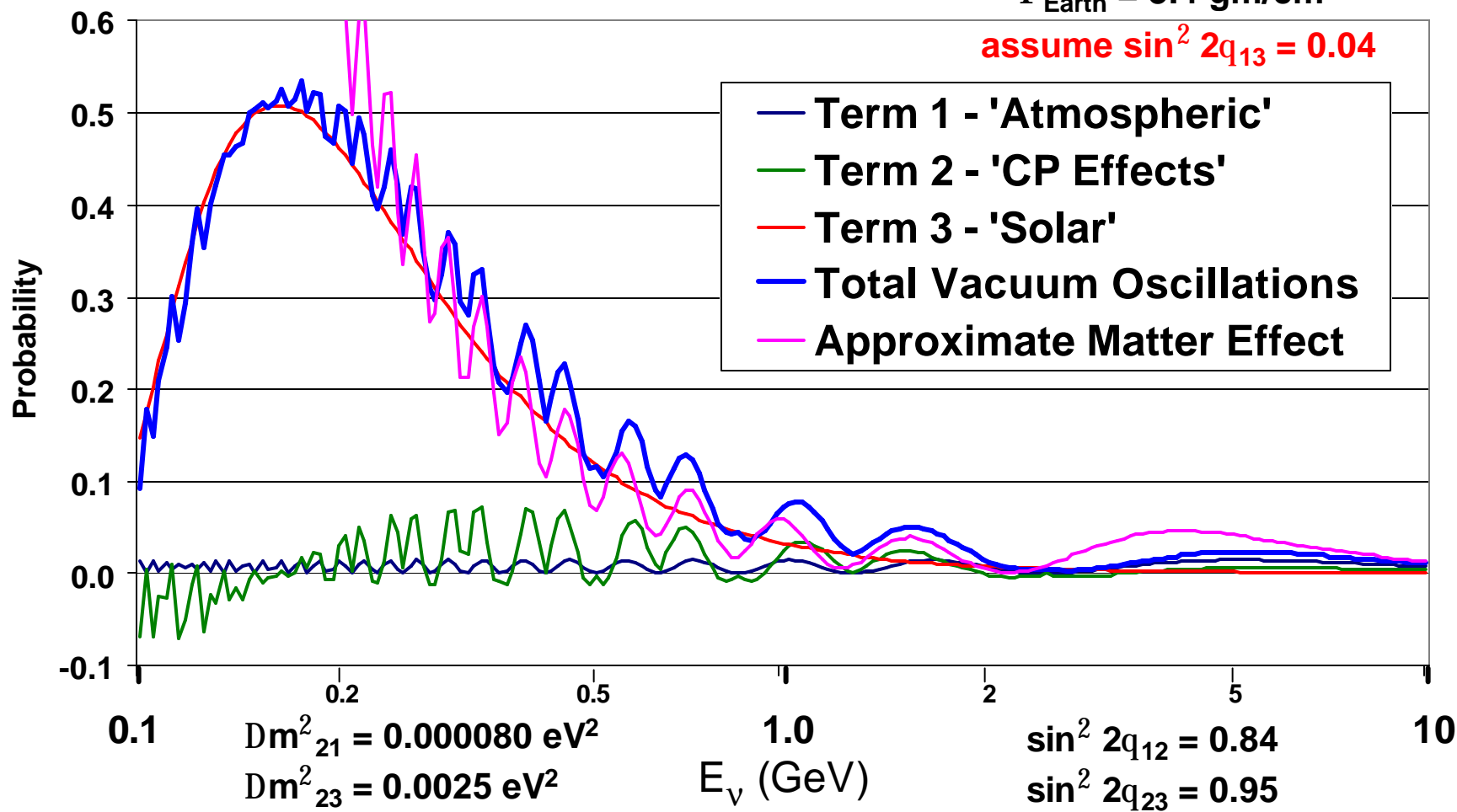[a] W. Marciano, Nuclear Physics B (Proc. Suppl.) 138, (2005) 370-375

Electron Neutrino Appearance by Oscillation in Vacuum

$\nu_\mu \to \nu_e$ Vacuum Oscillations - VLBNO
L = 2540 km

ρ_{Earth} = 3.4 gm/cm^3

assume $\sin^2 2\theta_{13}$ = 0.04

- Term 1 - 'Atmospheric'
- Term 2 - 'CP Effects'
- Term 3 - 'Solar'
- Total Vacuum Oscillations
- Approximate Matter Effect

Δm^2_{21} = 0.000080 eV^2

Δm^2_{23} = 0.0025 eV^2

$\sin^2 2\theta_{12}$ = 0.84

$\sin^2 2\theta_{23}$ = 0.95

E_ν (GeV)

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Electron Neutrino Appearance With Matter Effects

The oscillation for $\nu_\mu \rightarrow \nu_e$, including the *matter effect*, is given approximately by[a]:

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2((A-1)\Delta)/(A-1)^2$$

$$+ \, a \, 8 \, J_{CP} \sin(\Delta) \sin(A\Delta) \sin((1-A)\Delta) / (A (1-A))$$

$$+ \, a \, 8 \, I_{CP} \cos(\Delta) \sin(A\Delta) \sin((1-A)\Delta) / (A(1-A))$$

$$+ \, a^2 \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(A\Delta) / A^2$$

$$J_{CP} = \sin(\delta_{CP}) \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{13}) / 8$$

$$I_{CP} = \cos(\delta_{CP}) \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{13}) / 8$$

$$a = \Delta m^2_{21} / \Delta m^2_{31} \, ; \quad \Delta = \Delta m^2_{31} L/4E_\nu \, ; \quad A = 2VE_\nu / \Delta m^2_{31} \, ; \quad \Delta m^2_{31} \equiv m^2_3 - m^2_1$$

$$V = \sqrt{2}G_F n_e \, ; \quad n_e \text{ is density of electrons along the path}$$
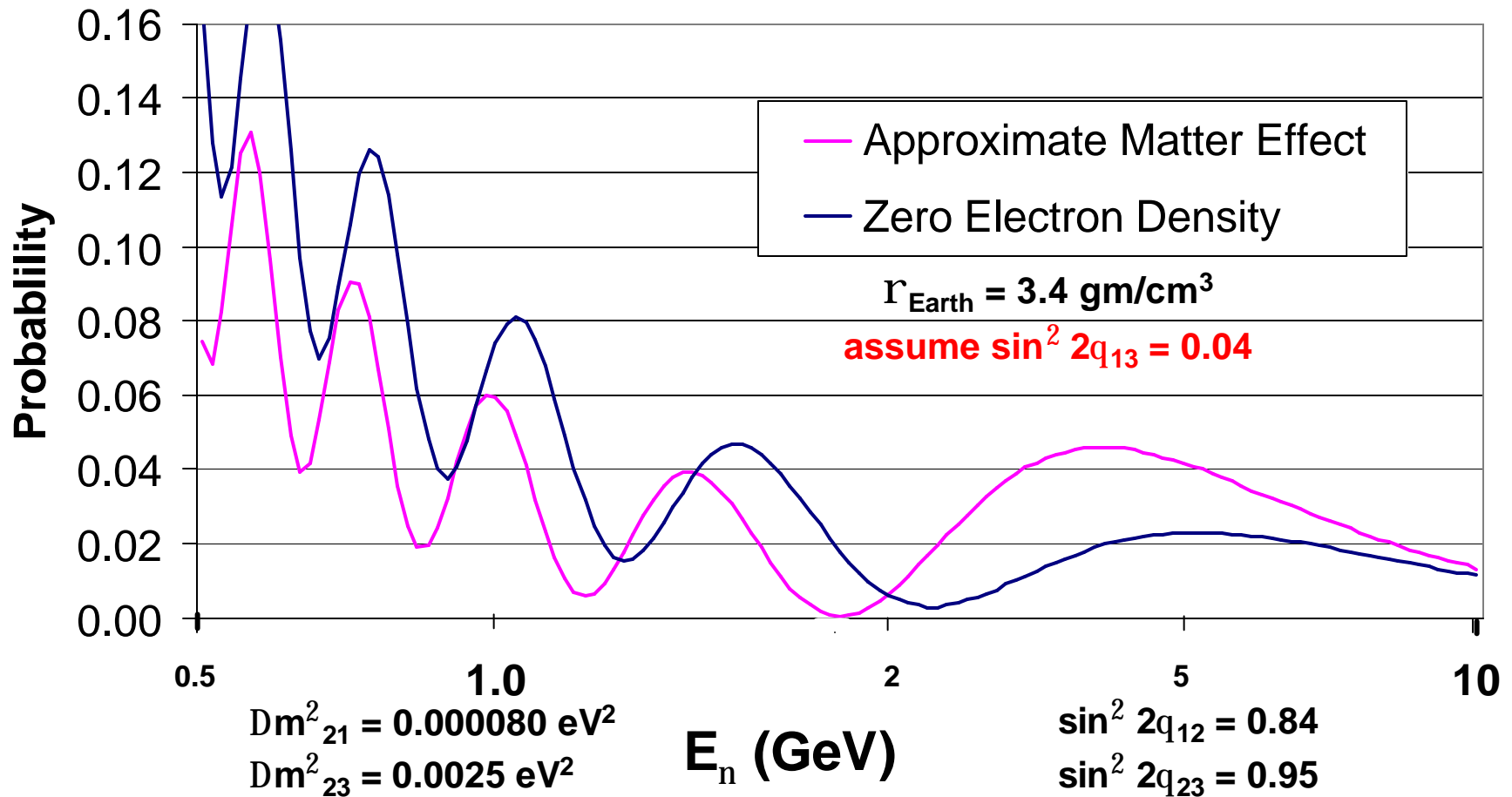
This expression separates terms by the the following:

 - **the first three terms show the effect of $\sin^2(2\theta_{13})$**
 - **the second and third terms show the effects of CP symmetry**
 - **the J_{CP} term changes sign when calculating anti-neutrinos, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$**
 - matter effects come into all terms via the 'A' factors in blue

[a] Barger et al.,Phys. Rev. D63: 113011 (2001); M. Freund, Phys. Rev. D64: 053003 (2001); Huber et al., Nucl. Phys. B645, 3 (2002); Barger et al. Phys. Rev. D65: 073023 (2002)

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Sensitivity to Matter Effect

$n_m -> n_e$ Matter Effects - VLBNO
L = 2540 km

Legend:
— Approximate Matter Effect
— Zero Electron Density

r_{Earth} = 3.4 gm/cm³

assume $\sin^2 2q_{13}$ = 0.04

Dm^2_{21} = 0.000080 eV²
Dm^2_{23} = 0.0025 eV²

$\sin^2 2q_{12}$ = 0.84
$\sin^2 2q_{23}$ = 0.95

Y-axis: Probablility
X-axis: E_n (GeV)

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Electron Neutrino Appearance – CP Phase Sensitivity
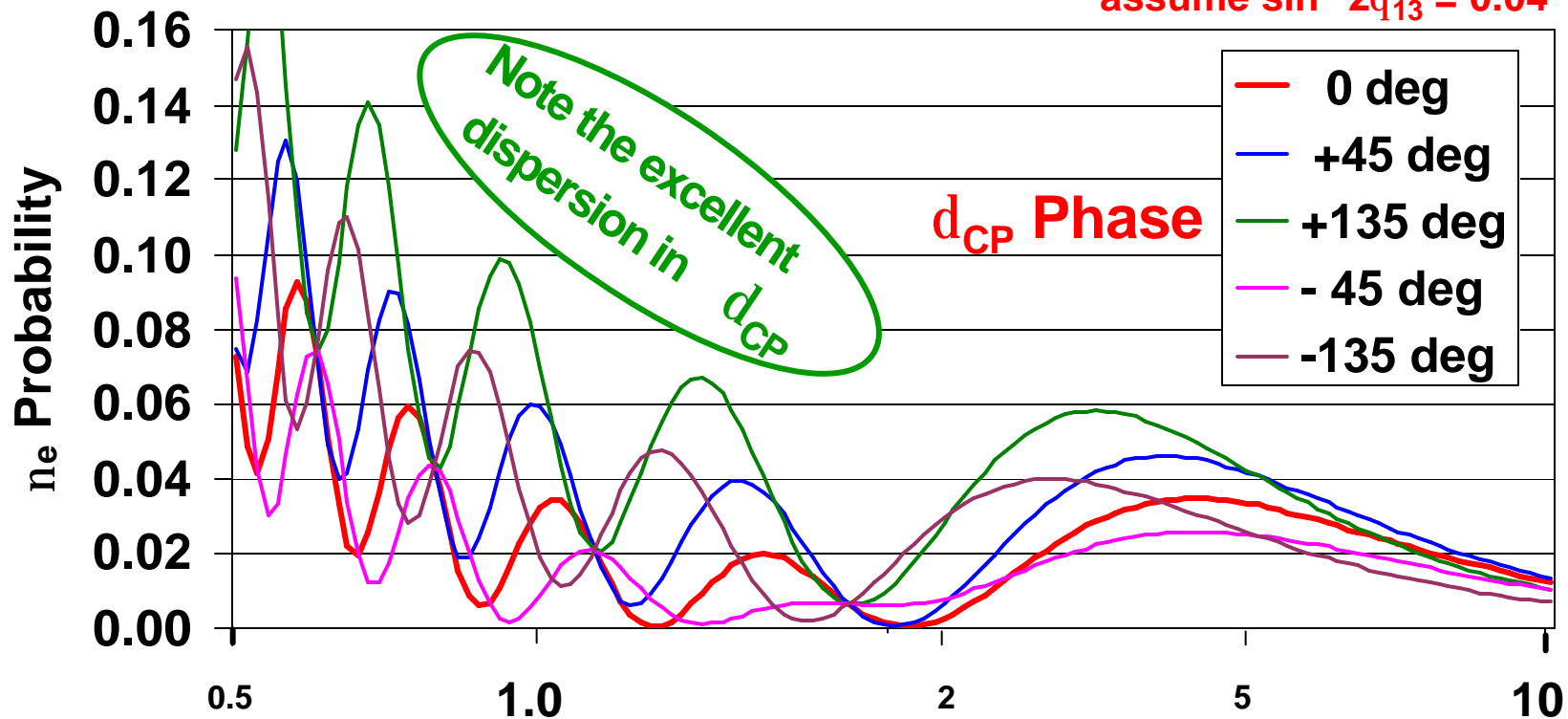
BNL ® Rocky Mountains *Super Neutrino Beam*

Homestake
2540 km

Henderson
2770 km

BNL

BNL ® Rocky Mountains enjoys a natural geographical advantage not present in other potential world sites
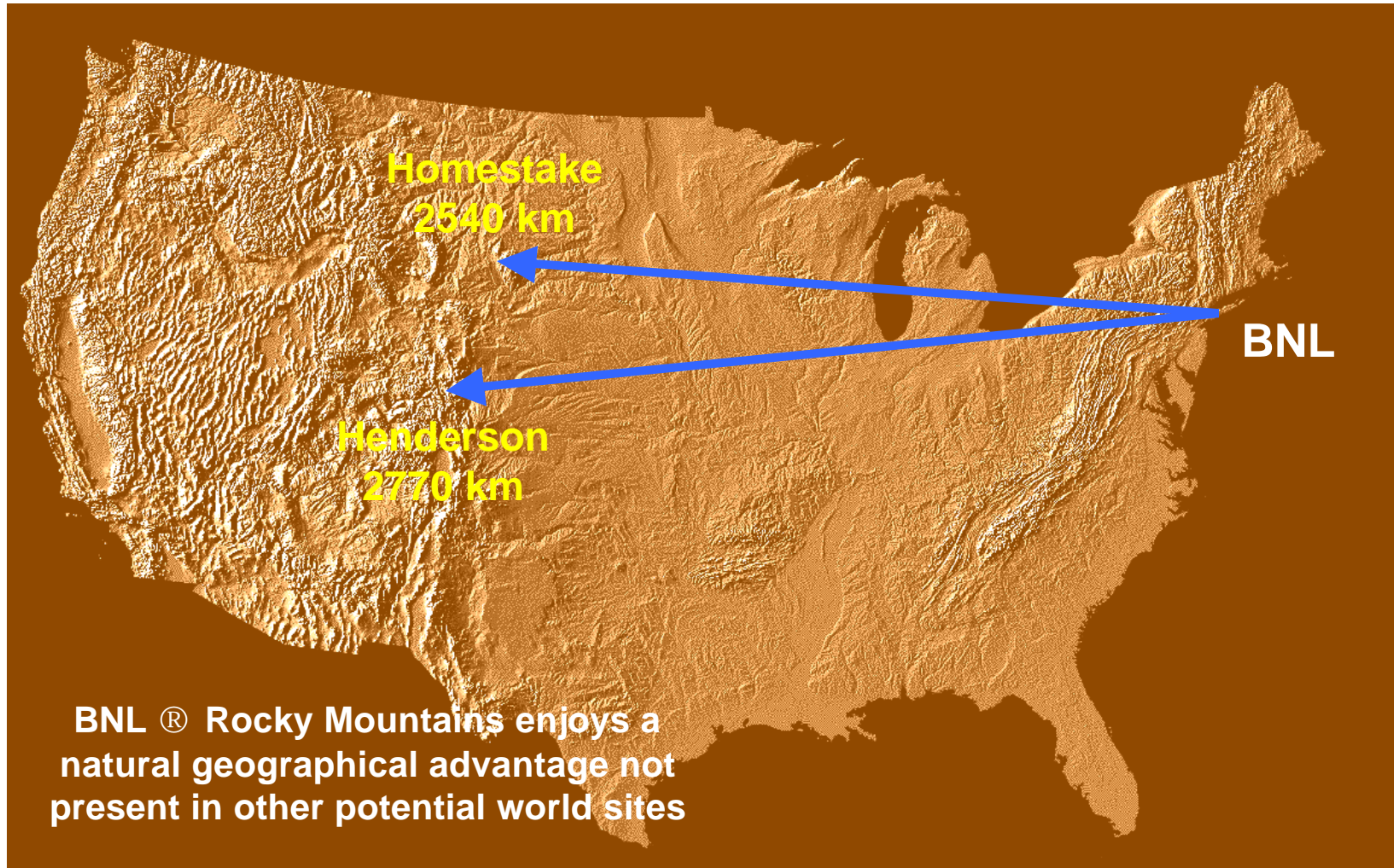
Very Long Baseline Neutrino Experiment

ν$_\mu$ DISAPPEARANCE

Events/bin vs Reconstructed ν Energy (GeV)

BNL-HS 2540 km

$\sin^2 2\theta_{23} = 1.0$

$\Delta m^2_{32} = 2e\text{-}3\ eV^2$

1 MW, 0.5 MT, 5e7 sec

No oscillations: 13290 evts

With oscillations: 5936 evts

Background: 1111 evts
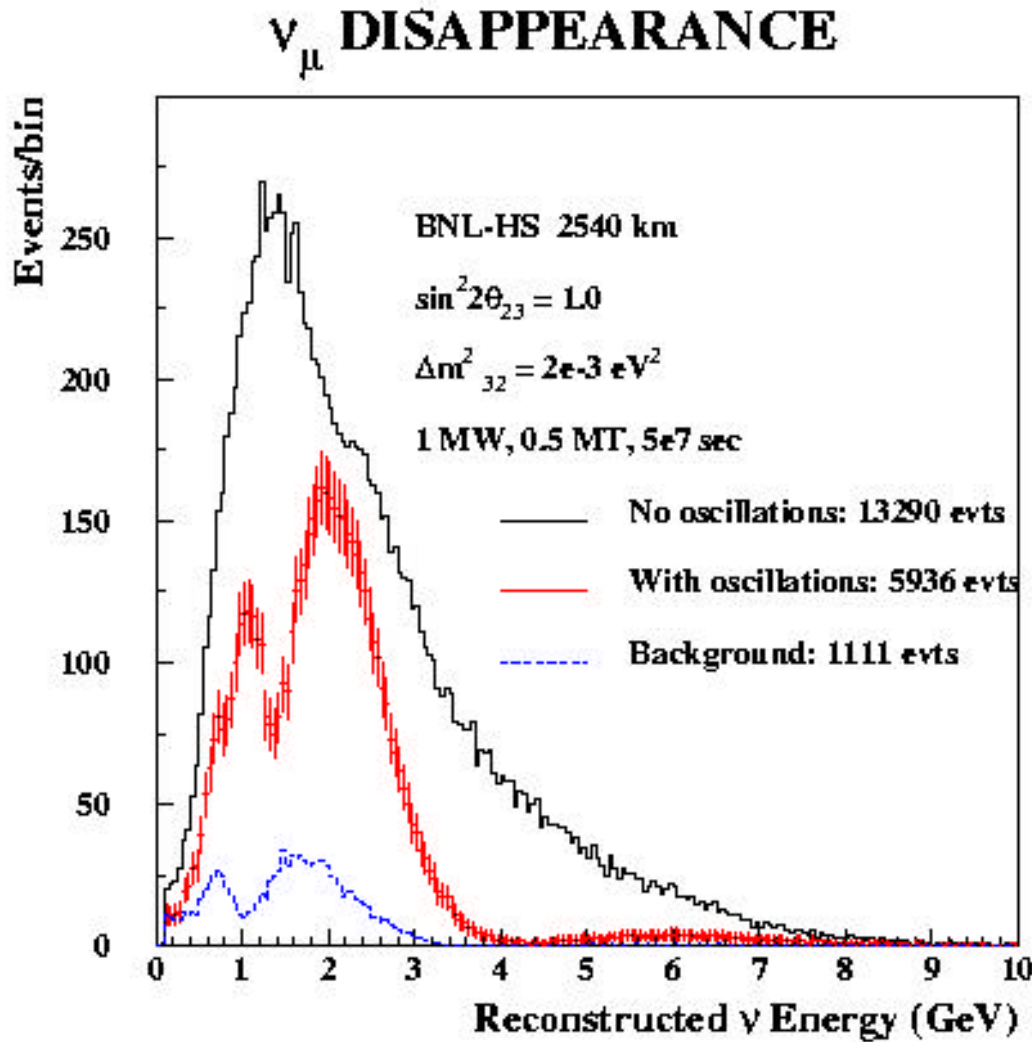
- neutrino oscillations result from the factor $\sin^2(\mathbf{D}m_{32}^2\ L\ /\ 4E)$ modulating the **n** flux for each flavor (here **n$_m$** disappearance)

- the oscillation period is directly proportional to distance and inversely proportional to energy

- with a *very long baseline* actual oscillations are seen in the data as a function of energy

- the multiple-node structure of the very long baseline allows the $\mathbf{D}m_{32}^2$ to be precisely measured by a *wavelength* rather than an amplitude (reducing systematic errors)

1-2 MW *Super Neutrino Beam* at AGS
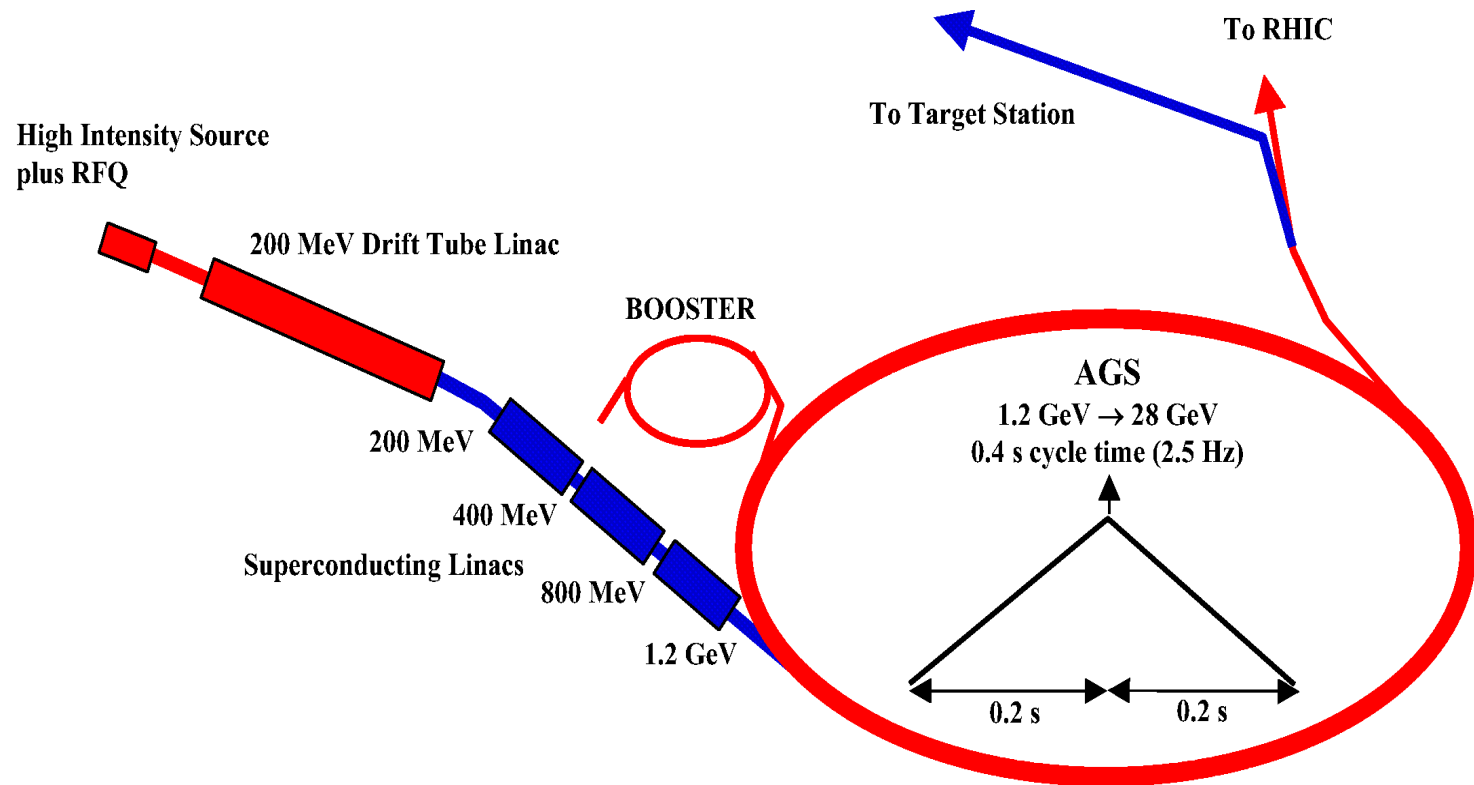
- BNL completed October 8, 2004, a Conceptual Design to support a new proposal to DOE to upgrade the AGS to 1-2 MW target power and construct the wide-band *Super Neutrino Beam* as listed in the DOE's "Facilities for the Future of Science" plan of November 2003

3-D *Super Neutrino Beam* Perspective

PROTON BEAM TRANSPORT (28 GEV)

U-LINE

POWER SUPPLY BUILDING

TARGET BUILDING

PION DECAY PIPE

POWER SUPPLY BUILDING

ACCESS ROAD

BEAM STOP

NEAR DETECTOR

NORTH

Signal/Background
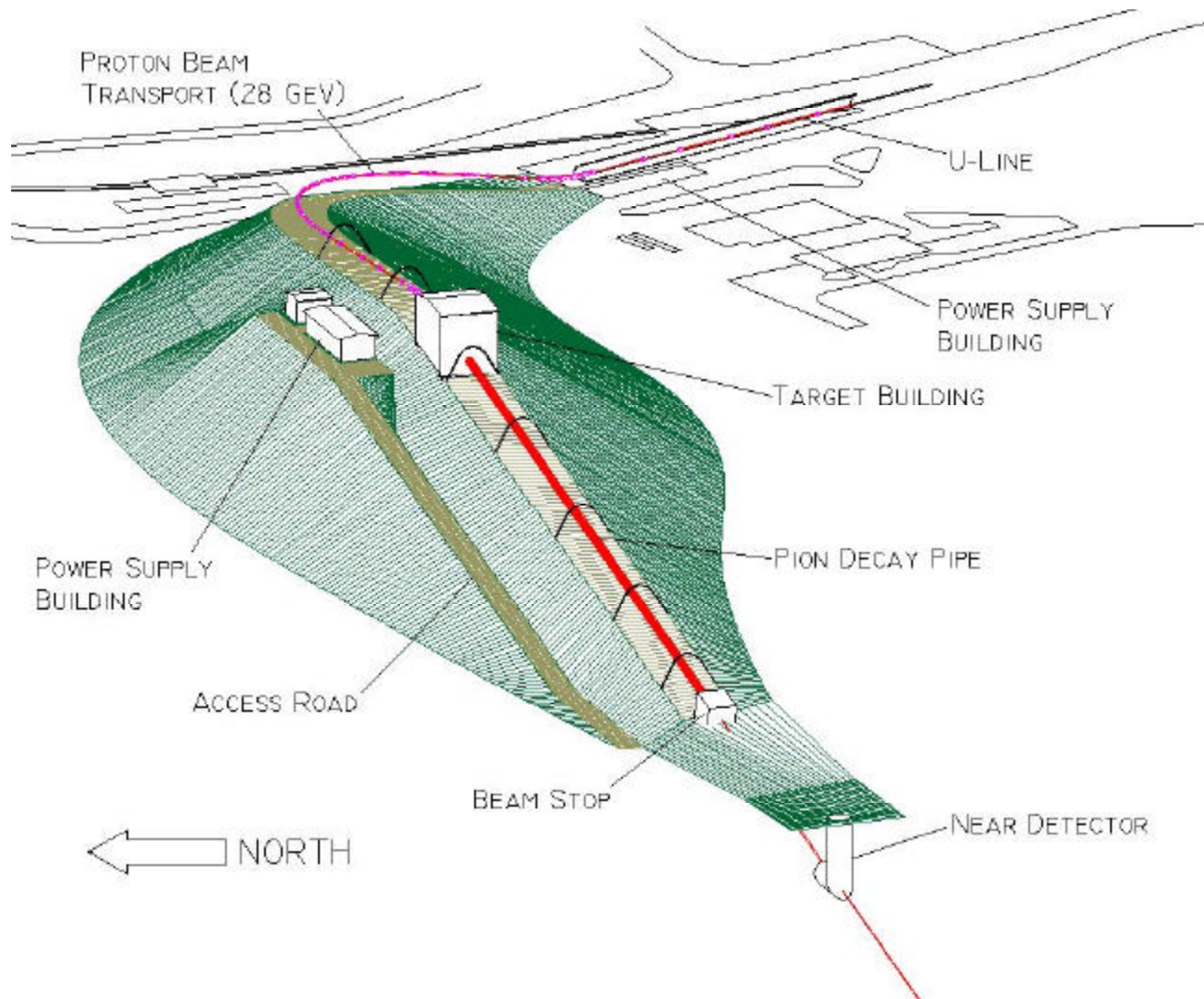
Effect of cut on Δ likelihood

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for background

No Δlikelihood cut (100% signal retained)　　　Δlikelihood cut (~50% signal retained)

Traditional Analysis

Preliminary

Background from π^0

ν_e background

CP+45°

Signal

E_{rec}
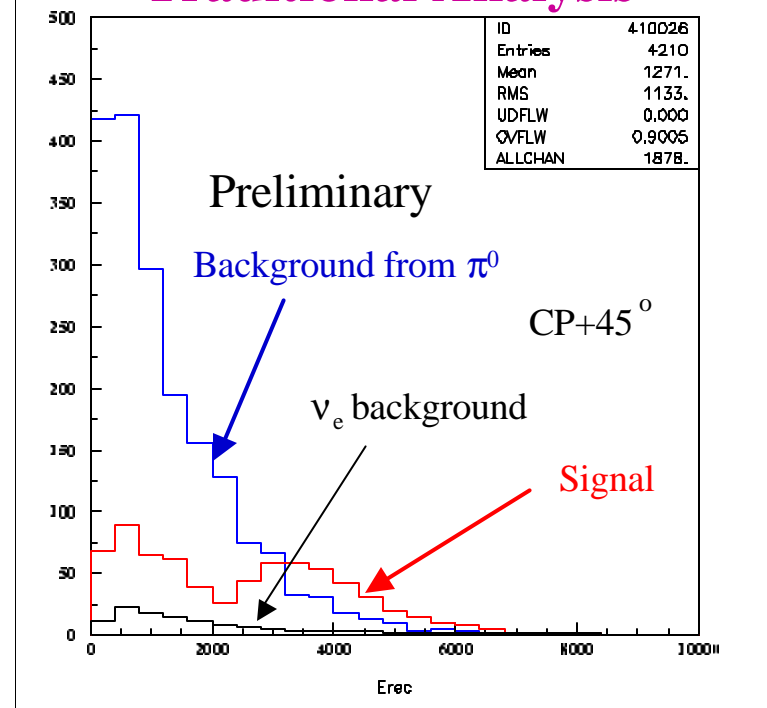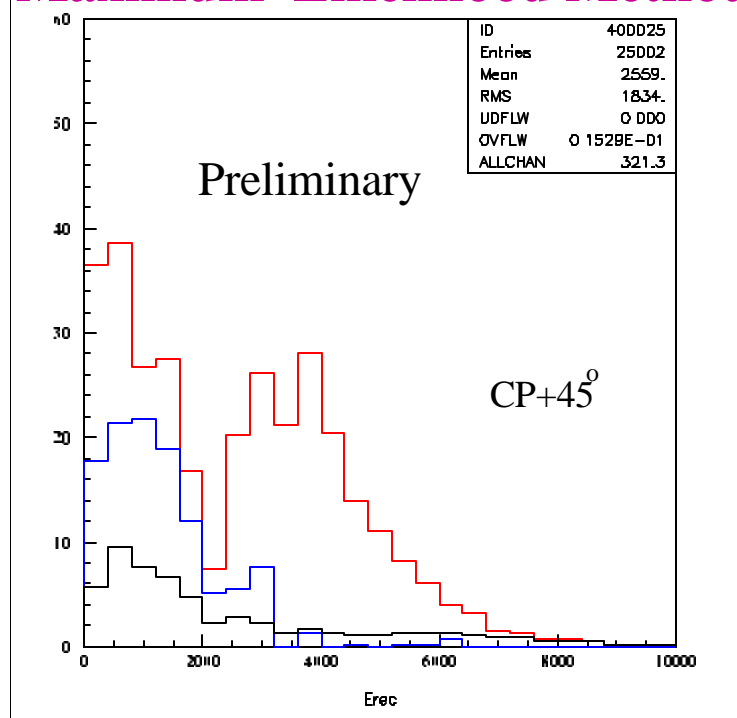
Signal 700 ev Bkgs 2005
(1878 from π^0+others)
(127 from ν_e)

Maximum Likelihood Method

Preliminary

CP+45°

E_{rec}

Signal 321 ev Bkgs 169
(112 from π^0+others)
(57 from ν_e)

Maximum Likelihood Method

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

- Effect of cut on likelihood

CP +45°

CP-45°
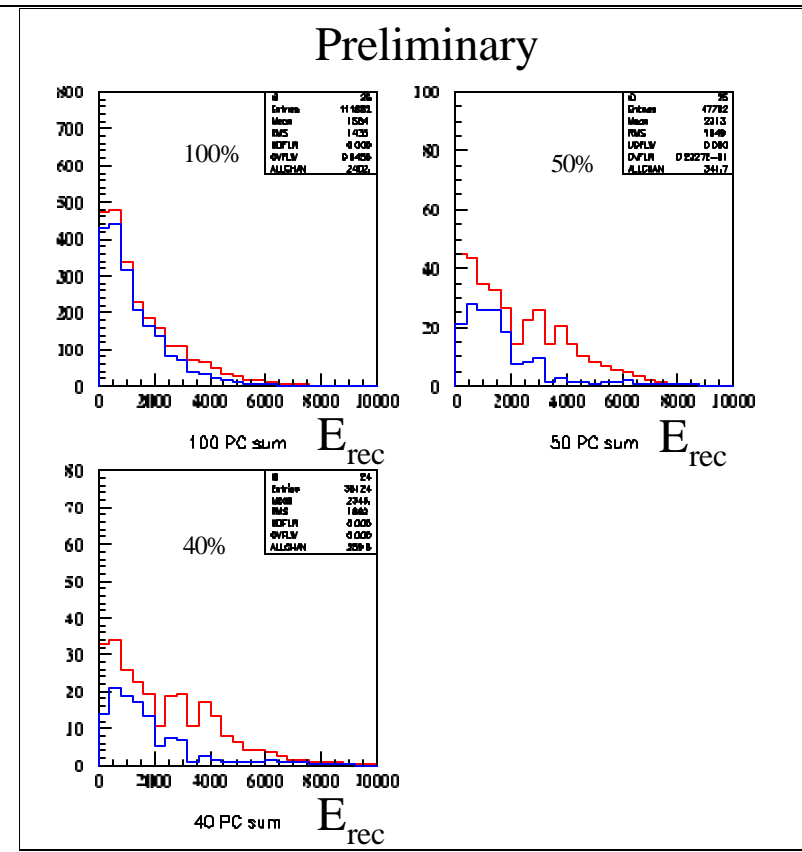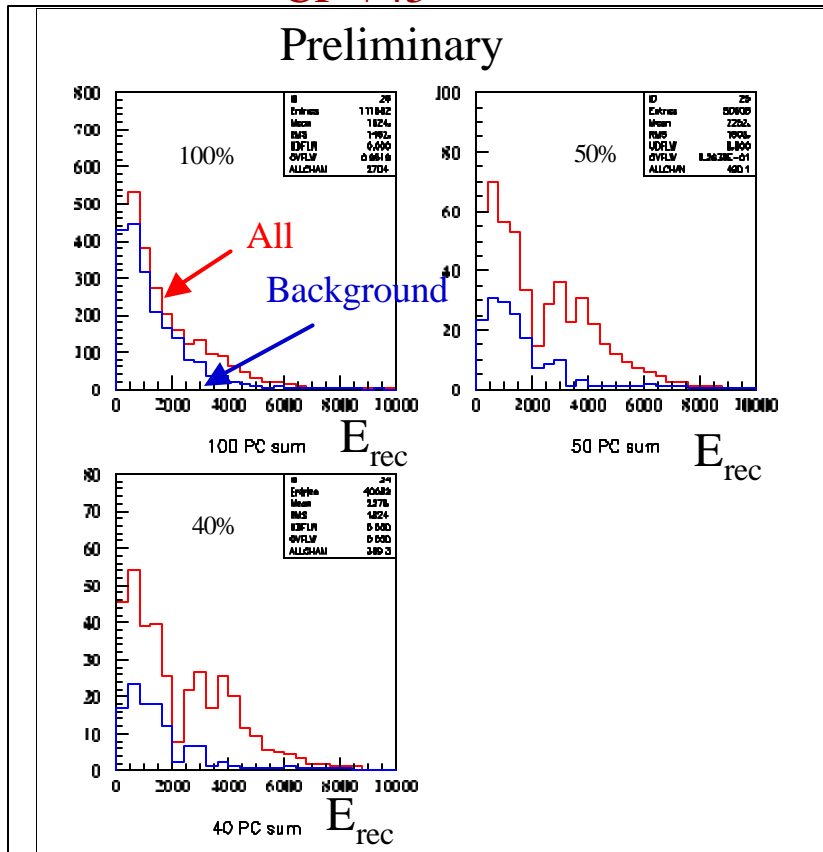
Chiaki Yanagisawa – SBU
February 28, 2005

Maximum Likelihood Method

- Effect of cut on likelihood

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

CP +135°

CP-135°

Preliminary
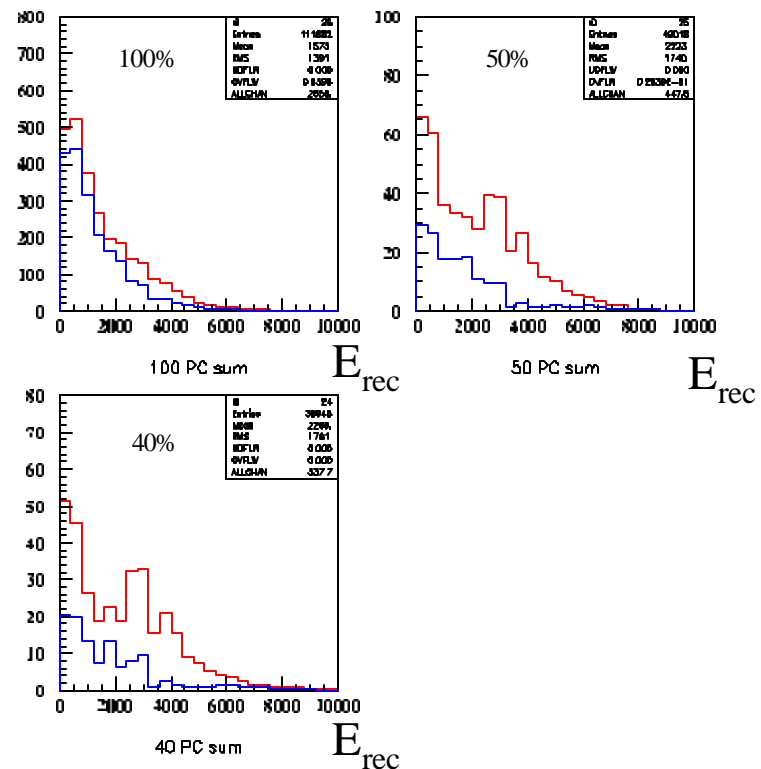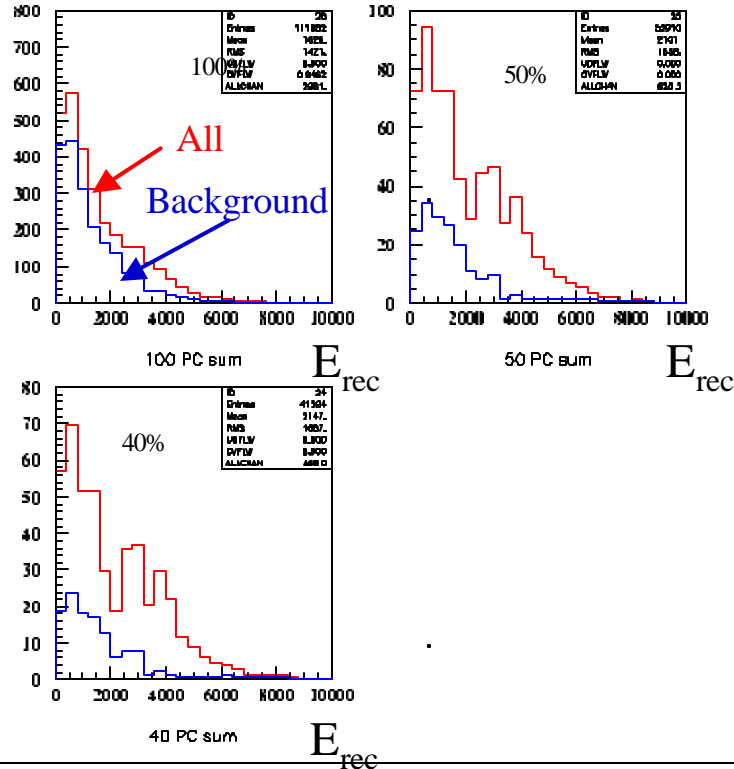
Preliminary

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Comparison of Future Neutrino Oscillations Exps.

Parameter	T2K	T2K2	Reactor	Noνa	Noνa2	VLBNO.
Δm_{32}^2	± 4 %	± 4 %	-	± 2 %	± 2 %	± 1 %
$\sin^2(2\theta_{23})$	±1.5 %	± 0.4 %	-	± 0.4 %	± 0.2 %	± 0.5 %
$\sin^2(2\theta_{13})$ [a]	>0.02	>0.01	>0.01	>0.01	>0.01	>0.01
$\Delta m_{21}^2 \sin(2\theta_{12})$ [b]	-	-	-	-	-	12 %
sign of (Δm_{32}^2) [c]	-	-	-	possible	yes	yes
measure δ_{CP} [d]	-	~20°	-	-	~20°	±13°
N-decay gain	x1	x20	-	-	-	x8
Detector (Ktons)	50	1000	20	30	30+50	400
Beam Power (MW)	0.74	4.0	14000	0.4	2.0	1.5
Baseline (km)	295 [e]	295 [e]	1	810 [e]	810 [e]	>2500
Detector Cost ($M)	exists	~1000	~20	165	+200	400
Beam Cost ($M)	exists	500	exists	50	1000	400
Ops. Cost ($M/10 yrs)	500	700	50	500	600	150/500 [f]

Both results needed to resolve ambiguities!

Best Bets

[a] detection of $\nu_\mu \otimes \nu_e$, upper limit on or determination of $\sin^2(2\theta_{13})$

[b] detection of $\nu_\mu \otimes \nu_e$ appearance, even if $\sin^2(2\theta_{13}) = 0$; determine θ_{23} angle ambiguity

[c] detection of the matter enhancement effect over the entire δ_{CP} angle range

[d] measure the CP-violation phase δ_{CP} in the lepton sector; Noνa2 depends on T2K2

[e] beam is 'off-axis' from 0-degree target direction;   [f] with/without RHIC operations

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Conclusions

- **Neutrino Oscillation parameters can be completely determined within the next two decades**

- **The most effective method is the *VLBNO + Wideband Super Beam***

- **A Megaton-class Water Cerenkov Detector can do this experiment**

- **The AGS-based Super Neutrino Beam is the best neutrino source**

- **Combining VLBNO with the *Nucleon Decay Search* in the *NSF DUSEL* is the most science and cost effective plan for the U.S.**

Electron Neutrino Appearance by Oscillation in Vacuum

$n_m \rightarrow n_e$ **Vacuum Oscillations - Nona**

L = 810 km

r_{Earth} = 3.4 gm/cm^3

assume $\sin^2 2q_{13}$ = 0.04

- Term 1 - 'Atmospheric'
- Term 2 - 'CP Effects'
- Term 3 - 'Solar'
- Total Vacuum Oscillations
- Approximate Matter Effect

Probability

E_ν (GeV)

Dm^2_{21} = 0.000080 eV^2

Dm^2_{23} = 0.0025 eV^2

$\sin^2 2q_{12}$ = 0.84

$\sin^2 2q_{23}$ = 0.95

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Sensitivity to Matter Effect

ν_μ -> ν_e Matter Effects - Nova

L = 810 km

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— Approximate Matter Effect
— Zero Electron Density

Probablility

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Electron Neutrino Appearance – CP Phase Sensitivity

ν_μ -> ν_e CP Phase Effects - Nona

L = 810 km

ρ_{Earth} = 3.4 gm/cm^3

assume sin^2 2q_{13} = 0.04

δ_{CP} Phase

Legend:
- 0 deg
- +45 deg
- +135 deg
- -45 deg
- -135 deg

ν_e Probability

E_ν (GeV)

Δm^2_{21} = 0.000080 eV^2
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Electron Neutrino Appearance by Oscillation in Vacuum

$$n_m \rightarrow n_e \quad \text{Vacuum Oscillations - T2K Exp.}$$
$$L = 295 \text{ km}$$

$r_{Earth} = 3.4 \text{ gm/cm}^3$

assume $\sin^2 2q_{13} = 0.04$

Legend:
- Term 1 - 'Atmospheric'
- Term 2 - 'CP Effects'
- Term 3 - 'Solar'
- Total Vacuum Oscillations
- Approximate Matter Effect

Y-axis: Probability (from -0.1 to 0.6)

X-axis: E_ν (GeV) (from 0.1 to 10)

$Dm^2_{21} = 0.000080 \text{ eV}^2$

$Dm^2_{23} = 0.0025 \text{ eV}^2$

$\sin^2 2q_{12} = 0.84$

$\sin^2 2q_{23} = 0.95$

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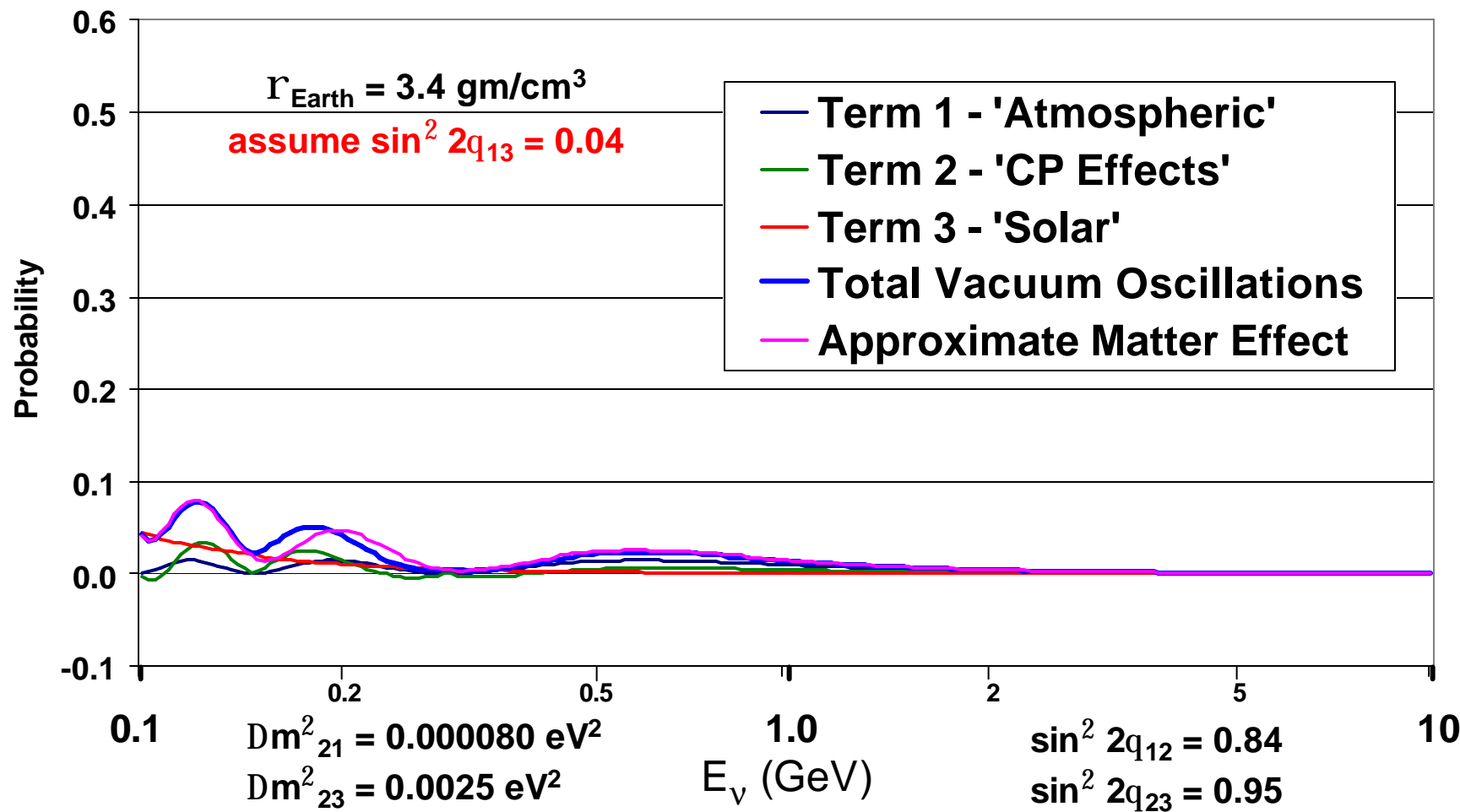
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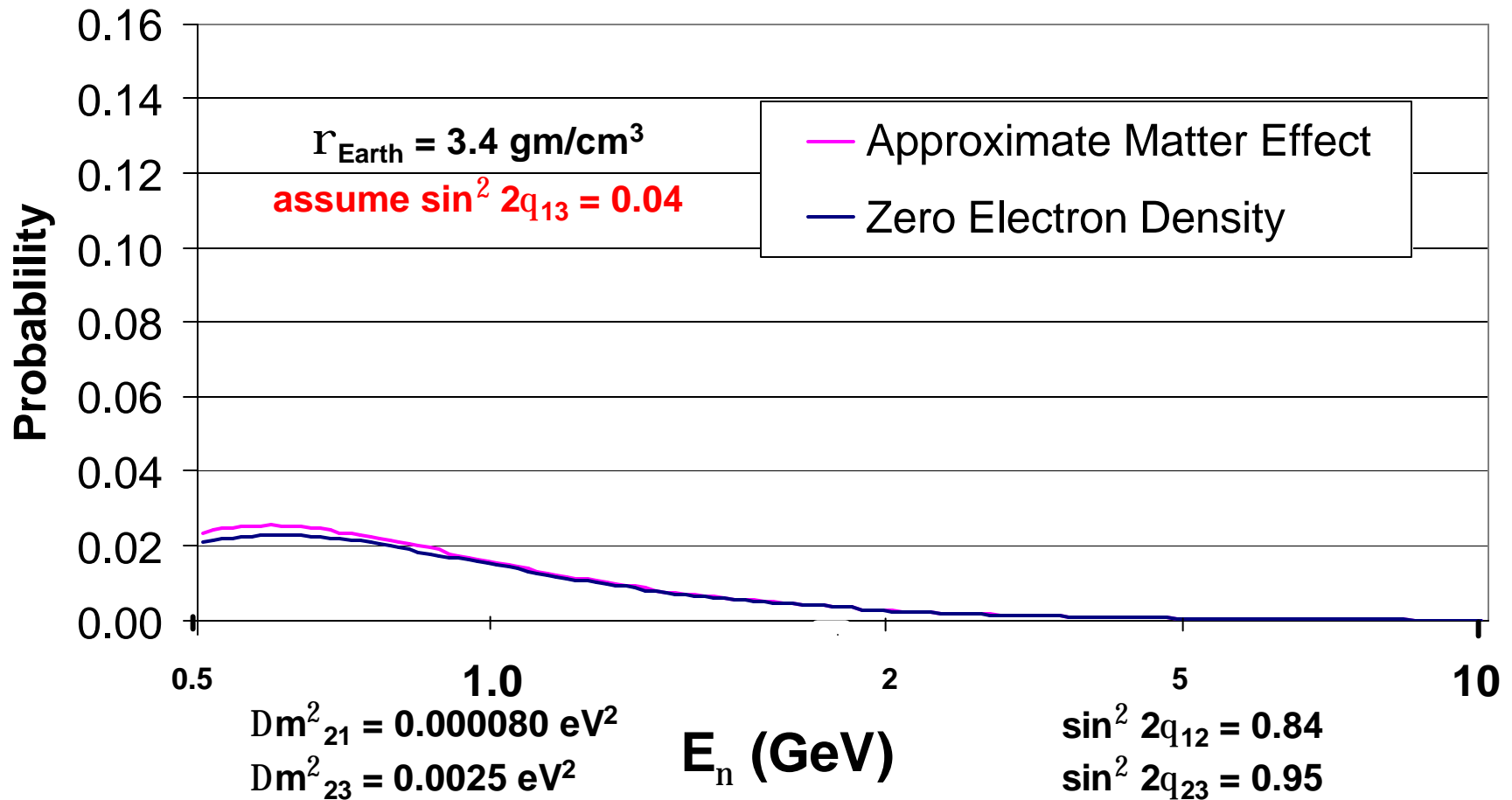
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$\nu_\mu \rightarrow \nu_e$ CP Phase Effects - T2K Exp.

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δ_{CP} Phase

- 0 deg
- +45 deg
- +135 deg
- - 45 deg
- -135 deg

ν_e Probability

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E$_\nu$ (GeV)

sin^2 2θ_{12} = 0.84
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